Regularizing the ODF estimate with the Laplace-Beltrami operator in 3D Polarized Light Imaging

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Abstract: 3D-PLI is an optical imaging approach that utilizes the birefringence in postmortem tissue to map its spatial fiber structure at a submillimeter resolution [1]. Recently Axer et al. proposed an estimate of the fiber orientation distribution functions (*pliODF*) from high-resolution PLI vector data. However, this technique introduces angular errors which, in turn, constrains the spherical harmonics (SH) expansion order. Here, we overcome this limitation by making use of the Laplace-Beltrami operator to analytically regularize the SH coefficients which define the fiber ODF at higher orders.

1 3D Polarized Light Imaging

Polarization Birefringence

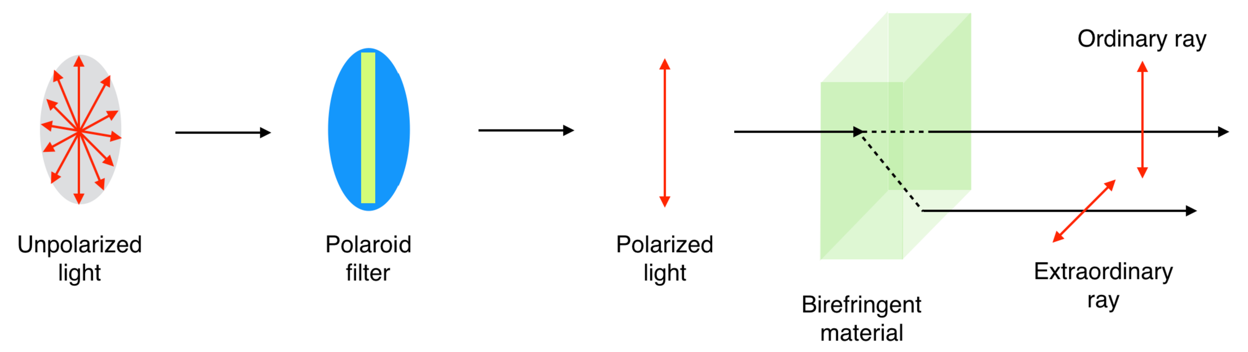


Image acquisition and analysis

Linearly polarized light passes through the tissue section and allows to detect its birefringence. A set of intensity images is analysed through Fourier series to get fiber orientation (α,φ) in each voxel.

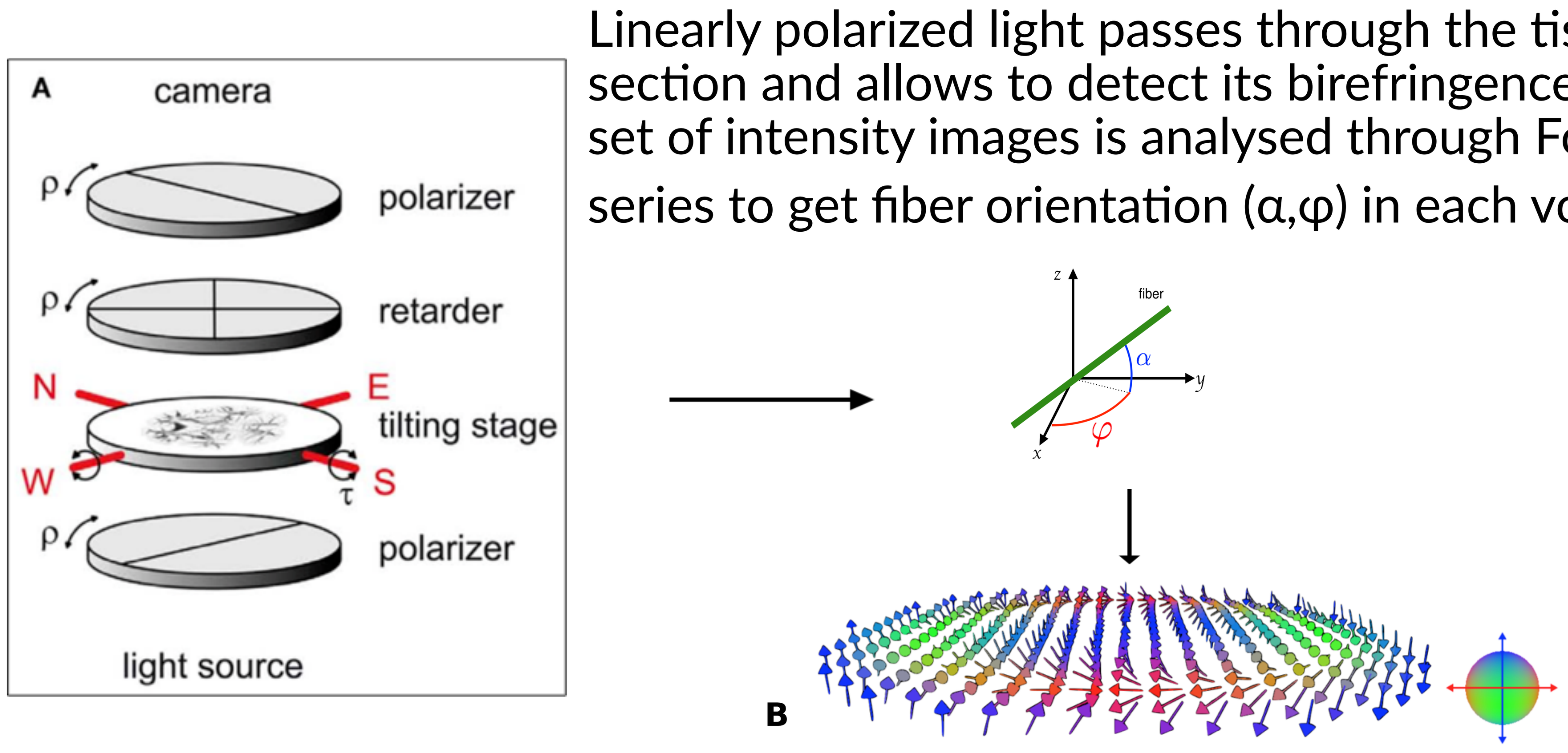


Image acquistion setup with tilting stage and different optic filters (A), from [1]. Each unstained histological section is characterized by a 3D vector field (B) visualized as a Fiber Orientation Map (FOM) at sub-millimeter resolution. The FOM is adapted from [2].

2 ODF reconstruction

pliODF [3]:

1. super-voxel for down-sampling high resolution FOM
2. normalized directional histogram (DH) on unit sphere
3. spherical harmonics expansion to approximate each DH

$$h(\theta,\phi) = \sum_{l=0}^{L_{max}} \sum_{m=-l}^{l} c_{lm} Y_l^m(\theta,\phi)$$

\+ bridging spatial scales: micro to macro

\- low odf angular resolution

Laplace-Beltrami regularization:

$$\Delta_b Y_l^m = -l(l+1)Y_l^m$$

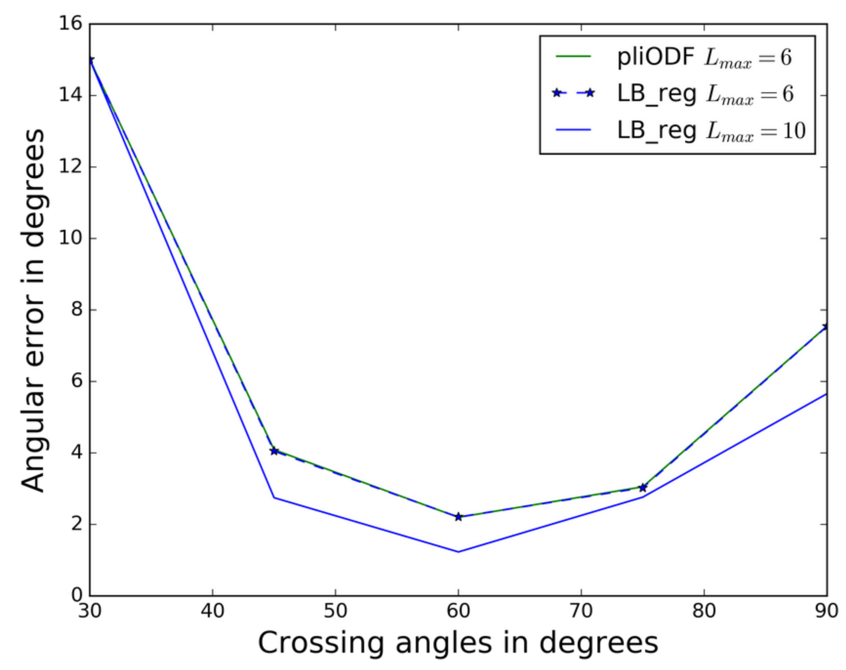
The SH bandlimit L_{max} is increased to sharpen the fiber ODF [4] and the regularized estimation of SH coefficients analytically writes

$$C = (B^T B + \lambda L)^{-1} B^T H$$

\+ bridging spatial scales

\+ higher angular resolution

\+ analytical solution

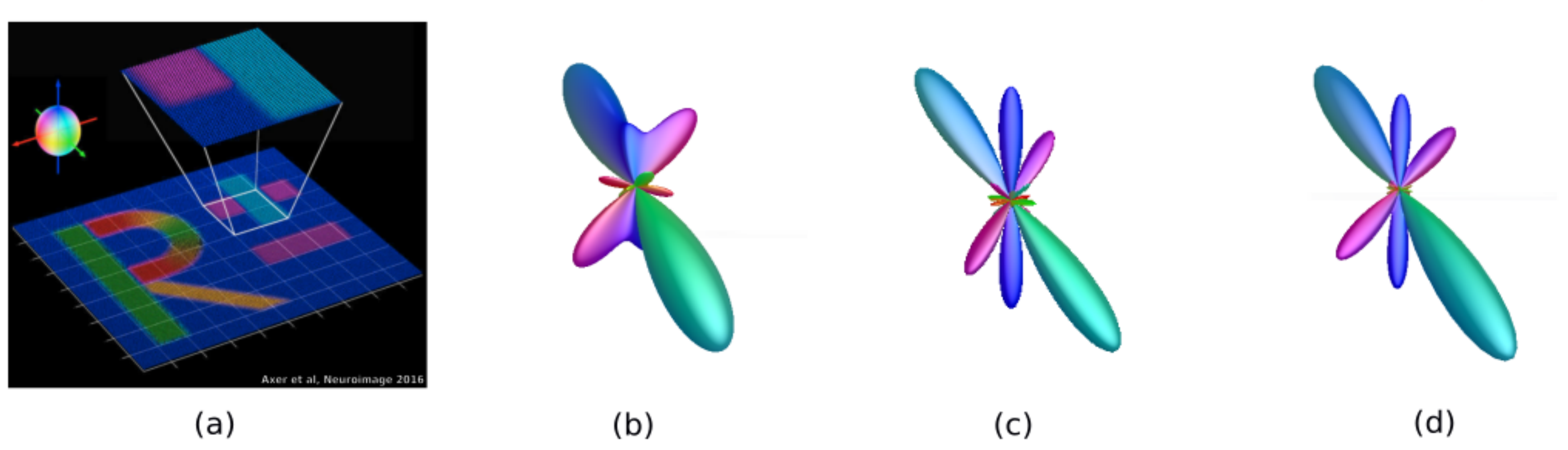


At L_{max} = 10 our regularized ODF produces less angular error than pliODF (error above 40° due to ill-conditionnned SH basis mattrix, not plotted)

3 Synthetic experiment

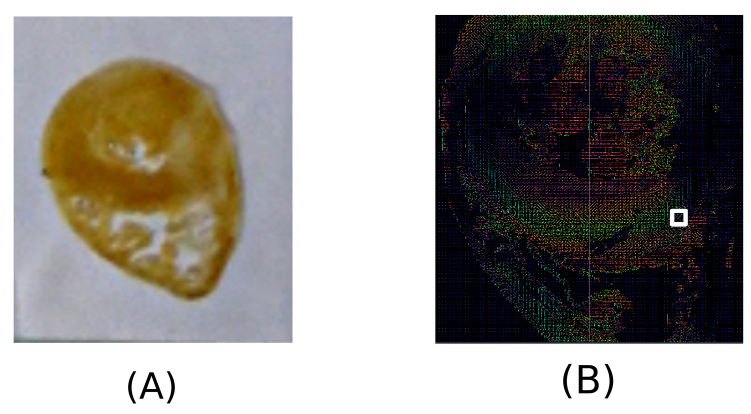
The performance of our approach is evaluated on the simulated dataset [3]. We choose a super-voxel (zoomed compartment) composed of 40 X 40 X 1 native voxels. 25% (in blue) oriented in (θ, φ) = (90°, 0°), 25% (magenta) in (−45°, 0°) and 50% (cyan) in (45°, 90°).

- Fiber ODF accurately reconstructed
- Angular resolution improved
- Volume fraction correctly estimated

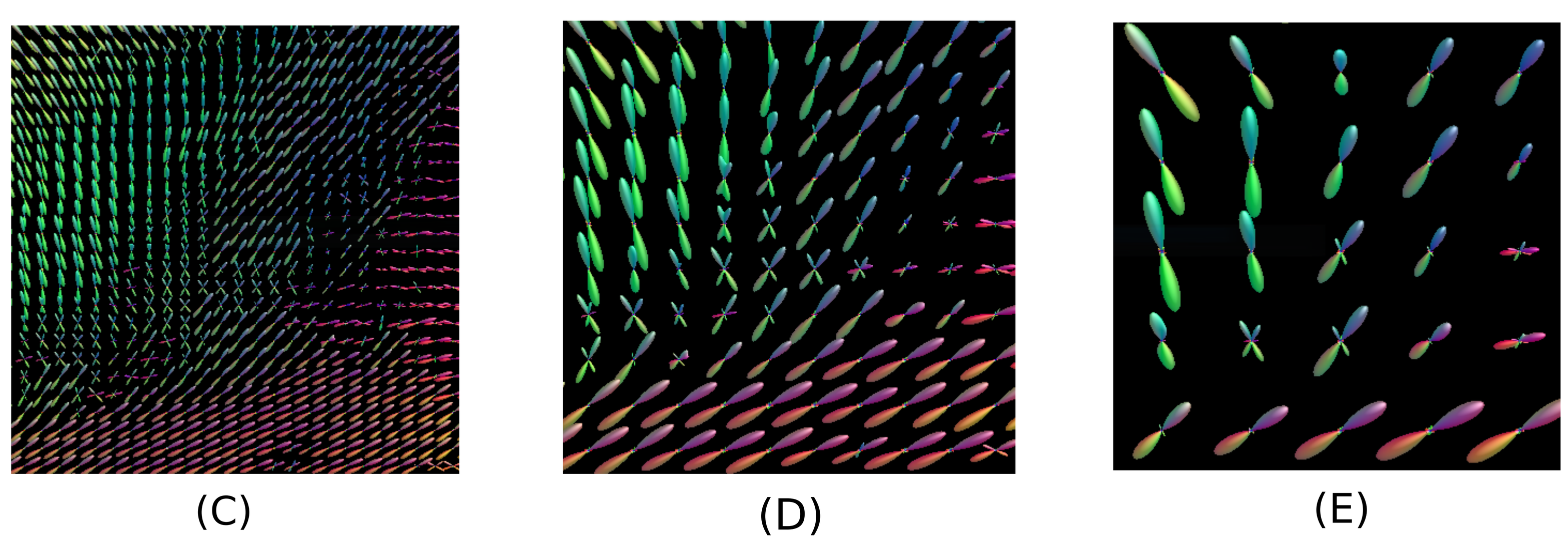


Fiber ODF generation: (a) simulated super-voxel from [3]. (b) pliODF at SH $L_{max=}$6, (c) and (d) Laplace-Beltrami regularized fiber odf at L_{max}=8 and 10, respectively. The three prevailling fiber orientation populations are preserved.

4 Ex-vivo human heart Data



Organ is frozen, sliced and imaged with no staining. Each FOM consists of high-resolution data of 440 X 620 voxels.



Coronal ventricular slice (A) with correspondnig high-resolution FOM (B). Fiber ODFs from the white rectangular RIO are reconstructed at different spatial scales defined by the super-voxel size: (C) 2 X 2X 2, (D) 5 X 5 X 2 and (E) 10 X 10 X 2 native voxels.

5 Discussion and Conclusions

- The Laplace-Beltrami regularization provides an analytical solution for the SH coefficients which define the fiber ODF.
- Compared to pliODF, our regularized ODF enhances the underlying angular resolution and considerably improves the extraction of fibers, eventually for tractography.
- This method is, however, still limited by the arbitrary discretization of the directional histogram.
- The concept of super-voxel allows data integration across scales: voxel-level comparison with diffusion MRI should now be possible.

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References

[1] Axer M et al, Neuroimage, 2011. [2] Dohmen M, PhD thesis, 2014. [3] Axer M et al, Frontiers in neuroanatomy, 2016. [4] Descoteaux M et al, Magnetic Resonance inMedicine, 2007.